Final Synopsis

On

"Investigation of Dielectric Properties of Sodic Soil at C-Band Microwave Frequency"

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1. Introduction

Soil quality plays an important role in agricultural productivity and environmental stability. It refers to the soil's ability to support plant growth, retain moisture, supply nutrients, and allow air and water movement. A well-structured and nutrient-balanced soil can help maintain food production and reduce environmental degradation. However, improper irrigation practices, excessive chemical inputs, and climate-related factors have contributed to widespread soil degradation. One of the common forms of degradation is sodicity, which alters both the physical and chemical characteristics of soil. Sodic soils are defined by a high proportion of exchangeable sodium ions (Na^+) on the soil particles. This sodium accumulation causes dispersion of clay, leading to poor aggregation, surface crusting, reduced permeability, and restricted root growth. As a result, sodic soils have low water infiltration, high pH, and limited nutrient availability. These conditions hinder plant development and reduce agricultural output, especially in semi-arid and irrigated regions.

Monitoring the condition of sodic soils is necessary to support land reclamation and sustainable farming. Traditional soil analysis methods such as chemical testing and manual sampling are time-consuming and limited in area coverage. In contrast, microwave remote sensing offers a rapid and non-destructive technique for assessing soil properties across large landscapes. This method depends on how soil interacts with electromagnetic radiation, which is governed by its dielectric properties. The dielectric properties of soil include the real part of permittivity (ε'), which indicates the soil's capacity to store electrical energy, and the imaginary part (ε''), which represents energy losses due to conductivity and relaxation processes. These properties are strongly influenced by soil moisture, salinity, texture, and structure. Therefore, they are used as indicators to detect and classify soil conditions using remote sensing.

Microwave frequencies in the C-band range (4–8 GHz) are especially useful in soil studies because of their moderate penetration depth and sensitivity to surface changes. Satellites like Sentinel-1 and RISAT-1 use C-band synthetic aperture radar (SAR) to collect data even under cloudy or rainy conditions. Studies have shown that changes in soil moisture, surface roughness, and ion concentration can be detected through variations in backscattered microwave signals at this frequency band [2], [3]. Despite advancements, there is limited research focused specifically on the dielectric properties of sodic soils. Most models used in soil dielectric studies were developed for general or saline soils, which behave differently from sodic soils. In sodic soils, poor structure and high sodium content reduce water retention and change the way electromagnetic waves interact with the surface. This can lead to inaccurate interpretations if standard models are applied without modification [4].

Previous research has attempted to improve dielectric models by including parameters related to salinity, moisture, and soil composition [5], [6]. However, more experimental data and localized studies are needed to account for the variability in sodic soils, especially in regions like central India, where such conditions are widespread.

This research aims to study the dielectric behaviour of sodic soils at C-band frequencies, using laboratory experiments and model analysis. It focuses on the relationship

between moisture content, sodium levels, and dielectric parameters. The goal is to provide better understanding for the development of remote sensing applications that can assist in soil classification, moisture estimation, and land management in sodicity-affected areas.

2. Review of Literature

Overview of Microwave Remote Sensing and Dielectric Theory

Microwave remote sensing, especially at frequencies in the L-, C-, and X-bands, has become an essential tool for Earth observation, offering the ability to retrieve critical geophysical parameters such as soil moisture, vegetation water content, and surface roughness. The core principle underpinning microwave sensing lies in the interaction between electromagnetic waves and the dielectric properties of surface materials. Dielectric permittivity governs the reflection, absorption, and transmission of microwaves in a medium, and its precise characterization is necessary for interpreting remotely sensed data.

Recent advances have demonstrated the significance of dielectric behaviour in various natural materials. For example, Dogan et al. (2020) investigated the dielectric properties of cherry leaves using waveguide methods over 3.30–7.05 GHz and applied curve-fitting models to describe variations due to moisture content. Their work highlighted the importance of dielectric models in vegetation monitoring. In soil research, Suman et al. (2021) evaluated multiple mixing models—Dobson, Hallikainen, Wang &Schmugge, and Mironov—against SMAP brightness temperature data to improve soil moisture retrieval accuracy, confirming that dielectric modelling is central to satellite-based soil observation.

Wu et al. (2022) proposed an advanced parameterization scheme for freeze-thaw conditions, which can significantly influence soil dielectric properties by altering unfrozen water content. Their model responds to seasonal variability, enhancing environmental monitoring accuracy. Similarly, Vine et al. (2022) established empirical relationships between salinity, temperature, and dielectric constants for seawater at L-band, aiding the development of ocean salinity sensors.

Studies in the cryosphere, such as those by Picard et al. (2022), introduced advanced scattering formulations that resolve inaccuracies in modelling snow and ice at varying densities. Tsang et al. (2022) further expanded the theoretical framework by incorporating hybrid full-wave models for microwave backscattering over forested and rough terrain, applicable to snow water equivalent and soil moisture estimation.

Dielectric theory also finds interdisciplinary application. Chiao et al. (2023) discussed its role in medical imaging, while Zawilski et al. (2023) emphasized calibration protocols for dielectric sensors to enhance soil water content estimation. Wang et al. (2024) introduced a maximum entropy production (MEP) approach to improve electromagnetic wave modelling for simultaneous moisture and vegetation retrieval. These contributions reflect the continued integration of dielectric theory into sensor design and environmental modelling.

Previous Studies on Soil Moisture Estimation and Dielectric Behaviour

Soil moisture plays a key role in hydrological, agricultural, and climatic processes. Andreasen et al. (2020) developed neutron transport simulations based on thermal-to-epithermal ratios to estimate soil moisture, showing that precise site-specific modelling significantly enhances moisture detection. Issa et al. (2021) applied time-domain reflectometry (TDR) for studying electrical properties in soil-like materials, contributing to new interpretations of TDR signals.

Sensor innovation continues to advance soil moisture estimation. Kaur et al. (2024) developed a circular split ring resonator (C-SRR)-based sensor to detect moisture-induced frequency shifts across varied soil types, achieving high sensitivity. Radar-based studies by Zribi et al. (2021) proposed reflectivity indices to link radar signals with soil roughness and moisture content. Velde et al. (2021) assessed SMAP satellite data against field measurements, highlighting the challenge of spatial scaling in translating point-level data to satellite pixels.

Upender et al. (2021) investigated scattering behaviour using bistatic scatterometry and observed dependencies on roughness, incidence angle, and soil water conditions. Szypłowska et al. (2023) evaluated the impact of temperature on complex dielectric spectra, emphasizing the need to correct for thermal effects when estimating soil moisture.

Aguiar et al. (2021) addressed water-dependent permittivity in GPR-based root detection, suggesting correction models for more reliable root diameter measurement. Yan et al. (2021) applied inverse modelling to TDR signals to derive high-resolution soil moisture dynamics, reinforcing the utility of capacitance-based models for precision agriculture.

Specific Studies on Salinity/Sodicity Effects and Models Used

Soil salinity and sodicity influence electrical conductivity, permeability, and vegetation health. Modelling these effects is critical for sustainable land management. Hassani et al. (2020) integrated climatic, topographic, and soil data with machine learning to predict salinity/sodicity dynamics at various scales. Their results emphasize the relevance of remote sensing–aided predictive modelling.

Zhang et al. (2021) used Landsat imagery and regression models to assess spatiotemporal variations in salinity in the Yellow River Delta. Zhu et al. (2022) applied UAV-mounted hyperspectral sensors with machine learning classifiers like Random Forest for band optimization, enhancing salt mapping precision.

Helalia et al. (2021) conducted controlled experiments and simulations to model salt accumulation in root zones, demonstrating how irrigation salinity and rainfall regulate seasonal salinity. Alamdar et al. (2023) extended this to arid regions using Landsat-8 and Random Forest models to generate large-scale salinity risk maps.

Zhao et al. (2023) utilized dielectric spectroscopy to identify frequency bands highly sensitive to salinity-induced changes in soil permittivity. Kramer et al. (2023) reviewed simulation models that incorporate climate variability and irrigation into salinity and sodicity forecasting.

Climate-driven modelling efforts are crucial in this context. Haj-Amor et al. (2023) applied HYDRUS-1D with climate models to project salinity evolution in rainfed maize fields. Song et al. (2024) used geographically weighted regression (GWR) to map spatial heterogeneity and causal factors of coastal salinity. These studies collectively confirm that integrating climate data, spectral imaging, and dielectric modelling yields robust and scalable salinity assessments.

Although existing dielectric mixing models—such as Dobson, Hallikainen, and Mironov—have been extensively applied for general soil moisture estimation, they exhibit limitations in addressing the unique electrochemical interactions in sodic soils. These models often assume homogeneity in texture and ignore ion-specific effects, especially those related to high sodium content, pH-induced dispersion, and structural breakdown.

Furthermore, few studies focus specifically on the dielectric characterization of sodic soils in the C-band frequency range. The effect of exchangeable sodium percentage (ESP), electrical conductivity (EC), and ionic strength on microwave interaction is poorly captured by current dielectric models. Additionally, empirical field validation of dielectric behaviour under natural sodic soil conditions, especially in semi-arid Indian districts like Buldhana, remains limited.

This study seeks to fill these gaps by performing a comprehensive dielectric analysis of sodic soil samples collected from Buldhana district at C-band frequencies (4–8 GHz). By correlating dielectric constants and losses with measured chemical parameters (pH, ESP, EC, Na^+), the work aims to establish a robust soil-specific dielectric model. It also addresses temperature effects, texture variability, and scattering behaviour—parameters often overlooked in conventional models. Ultimately, this research supports the development of improved classification frameworks and sensor calibration protocols tailored for sodic soils, enhancing microwave remote sensing applications for sustainable agriculture and land use planning.

3. Research Objectives

The primary aim of this research is to evaluate and model the dielectric behaviour of sodic soils in the C-band microwave frequency range, with implications for remote sensing and soil classification. The specific objectives are:

a) To calculate the emissivity, scattering, and reflectance of sodic soil, as these parameters are crucial for microwave remote sensing (MRS) of soil moisture.
b) To perform experimental measurements of complex dielectric properties of soil samples, specifically the real part (dielectric constant, ε') and imaginary part (dielectric loss, ε'').
c) To investigate these dielectric properties at C-band microwave frequencies (4–8 GHz) under controlled laboratory conditions, as a primary focus of the study.
d) To examine the effect of sodicity on the dielectric behaviour of soil and establish a linkage between electromagnetic properties and soil sodicity, which may help enhance soil sensor technologies.

e) To study the influence of physical parameters, particularly moisture content, on the dielectric response of sodic soils.
f) To compare the experimentally obtained dielectric data with existing dielectric models developed by researchers, in order to evaluate their applicability to sodic soil conditions.

4. Materials and Methods

4.1 Study Area and Sample Collection

The study was conducted across various locations in the Buldhana and Aurangabad districts of Maharashtra, India, which are known for their varying soil types and widespread occurrence of sodic conditions. These areas represent diverse agro-climatic zones, providing an ideal setting for examining the dielectric behaviour of sodic soils under different environmental conditions. Twenty-five soil samples were systematically collected from agricultural fields, roadsides, and village peripheries using standard augering tools. Each sampling site was geo-tagged using a Global Positioning System (GPS) to ensure spatial accuracy in data representation. The selection of sites was based on visible signs of sodicity, including surface crusting, poor vegetation, and whitish deposits, along with guidance from local agricultural experts. The table below lists the locations, latitude and longitude coordinates, and assigned sample numbers used for further analysis.

Table 1. GPS Coordinates and Locations of Sodic Soil Samples

Sample No.	Latitude	Longitude	Location
1	19.58881	75.78718	Ambad
2	19.60530	76.18178	Partur
3	19.63646	76.69244	Jintur
4	19.67563	75.32405	Bidkin
5	19.78450	76.41348	Khorad Sawangi, Mantha
6	19.81305	76.03158	Ramnagar
7	19.85048	74.83989	Vaijapur
8	19.87761	74.80963	Vaijapur
9	19.93117	76.05412	Nhava
10	19.94116	74.92785	Dhondalgaon
11	19.96169	75.16421	Devgad
12	19.96533	76.51381	Lonar
13	19.96639	75.68075	Somthana
14	19.97686	75.11620	Khultabad
15	19.99675	76.02734	Deulgaon Raja
16	20.03589	76.68835	Lonar
17	20.05734	76.52088	Mehkar
18	20.06025	76.47975	Mehkar
19	20.06451	75.69532	Phulambri
20	20.06963	75.95499	Butkheda
21	20.09688	75.51950	Phulambri

22	20.11738	76.54176	Mehkar
23	20.16667	76.38631	Sakharkharda
24	20.25899	76.10381	Chikhali
25	20.39131	76.23588	Chikhali

The collected samples were air-dried, sieved through a 2 mm mesh to remove debris and pebbles, and stored in labelled polyethylene bags for further laboratory analysis. These samples were later characterized for their dielectric properties using a C-band (4–8 GHz) microwave test bench, alongside moisture content and sodium concentration determinations, to correlate electromagnetic behaviour with physicochemical properties.

4.2 Physical & Chemical Analysis

Physical properties of the soil such as bulk density, porosity, water holding capacity, and particle size distribution (sand, silt, clay %) will be determined using standard methods, including the core method for bulk density and the hydrometer method for texture analysis. For chemical characterization, parameters such as pH and electrical conductivity (EC) will be measured using an electrometric method. Organic carbon will be tested using the Walkley-Black method. Macronutrients (N, P, K) and micronutrients (Zn, Fe, Cu, Mn, S, B) will be analyzed using the Harvesto Digital Soil Testing Kit and validated through standard laboratory protocols such as flame photometry, Olsen's method, and DTPA extraction.

4.3 Dielectric Measurements

Dielectric measurements will be performed using a C-band microwave test bench operating in the 4–8 GHz frequency range. The Von Hippel method in conjunction with a coaxial probe setup will be employed to evaluate the soil's electromagnetic response. The primary dielectric parameters to be recorded include the real part of permittivity (ε'), the imaginary part (ε''), loss tangent ($\tan\delta$), and electrical conductivity (σ). Additionally, secondary parameters such as resistivity (ρ), penetration depth (δp), quality factor (Q), and phase angle will be calculated based on the measured dielectric properties.

Data Analysis and Model Validation

Experimental data will be statistically analyzed to determine correlations between dielectric behaviour and key soil properties such as moisture content, sodium concentration, and texture. The measured dielectric values will be compared with established theoretical models (e.g., Dobson, Hallikainen, Mironov) to assess their applicability to sodic soils. Based on observed deviations, model calibration or refinement may be carried out to improve accuracy in predicting the dielectric response of sodic soils under field conditions.

5. Results and Discussion

5.1 Physical Properties

The physical characterization of the collected sodic soil samples demonstrated considerable variation in key parameters such as texture, porosity, bulk density, and water holding capacity. The bulk density (BD) of the samples ranged from 1.35 to 1.75 g/cm³, reflecting differences in compaction levels and organic matter content. Typically, soils with lower BD exhibited higher porosity and better structural conditions conducive to root development and

air–water movement. Porosity varied between 33.67% and 45.11%, with higher values generally observed in soils with elevated silt and clay fractions, enabling improved water and nutrient retention—an essential characteristic in moisture-stressed environments. The water holding capacity (WHC) ranged from 22.13% to 34.11%, largely influenced by clay percentage and organic matter content. Soils with fine textures and strong aggregation tended to retain more moisture. The soil texture classification indicated diverse compositions: sand content ranged from 40.12% to 63.78%, silt from 14.22% to 35.67%, and clay from 15.33% to 38.14%. These variations placed the soils in categories from loamy sand to clay loam, significantly affecting both their water retention potential and dielectric behaviour in the microwave frequency range.

5.2 Chemical Properties

The chemical analysis of the sodic soil samples provided valuable insights into their fertility status and sodicity-related constraints. The pH values ranged from 7.9 to 11.87, with many samples exhibiting strong alkalinity—a clear indicator of sodic conditions. Soils with pH levels above 9 often restrict nutrient availability and suppress microbial activity, thereby affecting plant growth. Electrical Conductivity (EC) values varied from 0.51 to 1.29 mS/cm, suggesting that while salinity was generally low to moderate, sodicity remains the dominant issue. The organic carbon (OC) content ranged from 0.16% to 1.66%, with numerous samples recording values below 0.5%, indicative of poor organic matter levels and reduced microbial biomass, ultimately limiting nutrient cycling and soil productivity.

Available nitrogen (N) content showed a wide distribution, ranging from 13.68 to 529.53 kg/ha. Extremely low nitrogen levels in some alkaline soils may be attributed to losses via volatilization and inhibited microbial nitrogen transformations. Phosphorus (P) and potassium (K) contents were also variable, ranging from 9.56 to 78.83 kg/ha and 7.27 to 328.76 kg/ha, respectively. In sodic soils, phosphorus deficiency is a recurring issue, often due to fixation under high pH conditions that render it unavailable to plants. The analysis of micronutrients revealed deficiencies of zinc, iron, and boron in several samples, which can be attributed to high soil pH and low organic matter—both factors that reduce micronutrient solubility and availability. These chemical characteristics collectively highlight the degraded fertility and nutrient imbalance commonly observed in sodicity-affected soils.

5.2 Dielectric Properties

The dielectric behavior of sodic soils was characterized using measurements of the real (ε') and imaginary (ε'') parts of permittivity at C-band microwave frequencies (4–8 GHz). These parameters are essential in understanding how sodic soils interact with electromagnetic waves, particularly for microwave remote sensing and soil moisture estimation.

1. Real Permittivity (ε'):

The real part of permittivity (ε'), indicating the soil's ability to store electrical energy, ranged from 3.30 to 4.26 across all samples. Higher ε' values were generally associated with increased moisture content and higher clay percentage, both of which enhance the soil's dielectric storage capacity. Soils with higher porosity and finer textures (e.g., higher clay content) also exhibited relatively elevated ε' values.

2. Imaginary Permittivity (ε″):

The imaginary part of permittivity (ε″), reflecting dielectric loss due to conductivity and relaxation mechanisms, ranged from 0.46 to 1.08. Soils with greater electrical conductivity (σ) and sodium content showed elevated ε″ values, suggesting that sodicity contributes significantly to energy loss mechanisms within the soil matrix.

3. Loss Tangent (tan δ):

The dielectric loss tangent ($\tan\delta = \varepsilon''/\varepsilon'$) varied between 0.11 and 0.27, indicating the relative efficiency of dielectric loss in each sample. High $\tan\delta$ values were observed in soils with higher moisture and electrolyte concentration, typical in sodic conditions. This implies increased signal attenuation, which is important for interpreting backscatter behavior in SAR remote sensing.

4. Electrical Conductivity (σ) and Resistivity (ρ):

Measured conductivity ranged from 0.14 to 0.33 S/m, with a corresponding inverse trend in resistivity, from 3 to 7 Ω·m. Soils with higher sodicity (as indicated by EC and Na^+ levels) displayed higher σ, confirming that ionic mobility and salinity influence the electromagnetic behavior of the soils.

5. Penetration Depth (δp):

The electromagnetic wave penetration depth ranged from 1.86×10^{-5} m to 4.32×10^{-5} m, indicating shallow penetration due to significant energy loss, especially in more conductive and moist soils. This limits the effective sensing depth of C-band SAR systems in sodic soils.

6. Quality Factor and Phase Angle:

The Q-Factor ranged from 3.7 to 8.8, inversely related to $\tan\delta$. A higher Q-Factor implies better energy storage relative to loss. The Phase Angle (– 6° to –15°) showed expected shifts in response to loss tangent and conductivity, reflecting changes in the dielectric relaxation behavior of the soils.

5.3 Influence of Moisture, Texture, and Sodium

The dielectric properties of sodic soils are significantly influenced by their moisture content, textural composition, and sodium levels. Moisture content plays a dominant role in enhancing both ε′ and ε″ values, as water molecules contribute to higher dipolar polarization and electrical conductivity. As moisture increases, the dielectric constant (ε′) rises due to greater free water availability, which intensifies the polarization response to the applied electromagnetic field.

Soil texture also modulates dielectric behaviour. Clayey and silty soils, due to their finer particles and larger surface area, retain more moisture and exhibit higher dielectric values. In contrast, sandy soils show lower permittivity because of their poor water-holding capacity. The presence of exchangeable sodium ions (Na^+) further affects dielectric loss (ε″), as sodium increases the ionic conductivity of the soil solution. Soils with high sodium content showed

elevated ε″ and loss tangent (tan δ), indicating greater energy dissipation and reduced transparency to microwave signals.

Overall, the combined effects of moisture, texture, and sodium content provide a comprehensive understanding of the soil dielectric response, which is essential for calibrating C-band remote sensing models aimed at detecting sodic and saline soils.

5.4 Comparative Model Evaluation

To interpret the measured dielectric properties, established dielectric mixing models—Dobson, Hallikainen, and Mironov were applied and evaluated for their predictive accuracy. Each model incorporates different assumptions regarding soil composition, water content, and texture interactions, making their comparative performance critical for remote sensing calibration.

The Dobson model, based on volumetric water content and soil texture, was found to slightly overestimate ε′ in high-salinity samples due to its limited sensitivity to ionic conductivity. The Hallikainen model, which uses empirical coefficients based on soil type, showed better alignment with the observed values for medium-textured soils, particularly in the ε′ range of 3.3 to 3.9.

The Mironov model, developed with improved consideration of bound water and salinity, exhibited the highest accuracy across all samples, especially for ε″. Its ability to incorporate dielectric loss due to ionic conduction made it more suitable for sodic conditions, where electrical conductivity significantly affects permittivity.

Model performance was assessed using statistical indicators such as the coefficient of determination (R^2), root mean square error (RMSE), and normalized mean bias. The Mironov model consistently yielded the lowest RMSE and highest R^2 values, supporting its application in calibrating microwave remote sensing data in sodic regions.

5.5 Implications for Remote Sensing

The dielectric characterization of sodic soils across the C-band frequency range (4–8 GHz) provides valuable insights for enhancing the accuracy of soil moisture retrieval in microwave remote sensing. The strong correlation between dielectric constants (ε′ and ε″) and soil moisture content supports the refinement of retrieval algorithms for Synthetic Aperture Radar (SAR) systems, particularly those operating within the C-band. This is critical for improving the reliability of soil moisture estimation in sodicity-affected regions where traditional methods may underperform due to complex surface conditions.

The findings are especially relevant for satellite missions such as Sentinel-1 (ESA), RISAT (ISRO), and SMAP (NASA), which rely on backscatter sensitivity to soil moisture variations. Incorporating region-specific dielectric data into calibration routines can enhance retrieval models by accounting for the unique dielectric behaviour of sodic soils. This has broader implications for agro-ecological monitoring, hydrological modelling, and precision irrigation planning in affected areas. Ultimately, these improvements can contribute to more informed decision-making in agricultural management and land reclamation strategies.

Conclusions

The present study successfully investigated the physical, chemical, and dielectric characteristics of sodic soils collected from various regions in Maharashtra. The physical properties revealed significant variability in bulk density, porosity, water holding capacity, and soil texture, indicating a heterogeneous nature of soil structure and compaction across different sites. The chemical analysis highlighted the strong alkalinity of many samples (pH > 9), low organic carbon, and deficiencies in key nutrients, especially nitrogen, phosphorus, and micronutrients such as zinc and iron—characteristics typical of sodic and degraded soils.

Importantly, the dielectric analysis at C-band (4–8 GHz) demonstrated that soil dielectric properties (ε', ε'', $\tan\delta$, σ) are strongly influenced by moisture content, salinity/sodicity levels, and texture. Higher sodium content and pH altered the permittivity values, which may impact the backscattering behaviour of microwave signals used in remote sensing. The experimental data generated serve as a valuable ground-truth reference for improving microwave remote sensing models, particularly for SAR-based soil moisture and sodicity mapping.

In summary, the study provides crucial insights into how sodic conditions affect electromagnetic responses of soils. These findings support the development of region-specific dielectric models and enhance the potential of C-band SAR sensors in environmental monitoring, precision agriculture, and land reclamation strategies.

Future Scope

Building on the insights from this study, several opportunities exist to further enhance the understanding and application of dielectric properties in sodic soil analysis:

a) **Seasonal Monitoring**: Future research can incorporate temporal variations by analyzing dielectric responses of sodic soils across different seasons, which will help understand moisture dynamics, salinity progression, and soil degradation patterns over time.

b) **Expanded Soil Types**: The methodology used in this study can be extended to other problematic soils, such as saline, acidic, or gypsiferous soils, to develop a comparative dielectric response framework applicable across diverse agro-ecological zones.

c) **Integration with Remote Sensing Platforms**: Dielectric data can be fused with satellite-based microwave observations (e.g., Sentinel-1, RISAT, SMAP) for large-scale, real-time soil moisture and sodicity mapping using advanced machine learning or inversion models.

d) **Development of Soil-Specific Calibration Models**: Further refinement of dielectric mixing models like Dobson, Mironov, and Hallikainen, tailored specifically for Indian sodic soils, can lead to more accurate parameter retrievals from SAR data.

e) **Portable Sensor Design**: The findings may contribute to the development of low-cost, field-deployable dielectric sensors or probes that offer real-time soil diagnostics, supporting precision agriculture and site-specific soil reclamation efforts.

f) **Soil Health and Reclamation Monitoring**: Dielectric properties can be used to monitor the effectiveness of gypsum and organic amendments in reclamation trials, helping assess changes in soil structure, porosity, and moisture retention during rehabilitation.

These future directions will not only strengthen dielectric-based soil assessment techniques but also enhance the precision of remote sensing applications for sustainable land and water resource management in sodic-prone regions.

Thesis Scheme

The present thesis is organized into the following chapters, each addressing key components of the research titled ***"Investigation of Dielectric Properties of Sodic Soil at Microwave Frequency at C-Band"*:**

Chapter 1: Introduction
Provides an overview of the research problem, outlines the objectives, and discusses the significance of studying dielectric properties of sodic soils, especially in the context of microwave remote sensing
.
Chapter 2: Literature Review
Reviews existing research on soil dielectric behaviour, microwave sensing technologies, and identifies research gaps related to sodic soil studies.
Chapter 3: Materials and Methods

Details the methodology used, including sample collection, preparation, physical and chemical analysis, dielectric property measurement, and instrumentation setup.

Chapter 4: Results and Discussion
Analyses the collected data on soil properties, interprets dielectric behaviour across different conditions, and discusses findings using tables, figures, and comparative models.

Chapter 5: Conclusion and Future Scope
Summarizes major conclusions, discusses practical applications, and suggests future research directions to enhance soil characterization and remote sensing techniques.

List Of Publications / Conferences Attended.

1. Farhat Shaheen Masood Khan , Dr. Kanti Zakde (May 2024) Publication : International Journal of Multi-physics
   Paper Name : Dielectric properties of Sodic Soil at C-Band : Analysis of permittivity, Loss Tangent and Conductivity.(UGC Care Journal)
   DOI : https://doi.org/10.52783/ijm.v18.1787

2. Farhat Shaheen Masood Khan, Gopinath Y Chavan, Nilkanth N Kapse, Vishal A Pandit, Dr. Kanti Zakde (April - 2025) International Journal : Metallurgical and Materials Engineering.(UGC CARE) Journal.
   Paper Name : Dielectric Characterisation of Sodic Soils in the C-Band : Implications for Moisture Monitoring . DOI: https://doi.org/10.63278/1289

3. Farhat Shaheen Masood Khan, Dr. Kanti Zakde (May - 2025) Presented and Published a paper : International E-Conference on Humanity , Technology and Environment : Multi Disciplinary Dialogues for Progress.
   Paper Name : Dielectric Characterisation of Sodic Soils in the C-Band Implication for soil Classification and Reclaim nation

4. Farhat Shaheen Masood Khan, Gopinath Y Chavan, Dr. Kanti Zakde Publication : International Journal of Scientific Research in Science and Technology
   Paper Name : C-Band Dielectric Characterisation of Sodic Soil : Implications for Soil Classifications and Reclamations Strategies.

5. Farhat Shaheen Masood Khan, Dr. Kanti Zakde (OCT– 2024) Conference : International E-Conference on :" Sustainability Approach : Role of Science And Technology
   Paper Name : Evaluation of Sodic Soil , Reclamation through Dielectric Constant Measurement in the C-Band Frequency Range.

6. Farhat Shaheen Masood Khan, Dr. Kanti Zakde (Jan - 2025) Conference : Presented Paper in International Conference on Harmony of Wisdom
   Paper Name : Impact of Physical Soil Properties on Microwave Emissivity And Reflectance in Sodic Soils at C-Band Frequencies.

References: A structured list of all books, journals, and reports referred to throughout the thesis, formatted as per scientific standards.

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